PREDICTED YIELDS OF SELECTED RADIOACTIVE NUCLEAR BEAMS FROM A THICK TARGET BOMBARDED BY HIGH ENERGY PROTONS

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SUMMARY

The yields of the shorter lived isotopes of He, Li, Na, Ar, K, Ga, Kr and Fr have been calculated for thick targets of tantalum, thorium and uranium bombarded with 1 GeV protons.

The calculations have used a theoretical model of the target to evaluate the diffusion and effusion time constants of the target and ioniser from measured release curves. A design of fast target has been proposed and the time constants extrapolated to this geometry. From these values, the release efficiencies of a number of selected short-lived isotopes have been determined. The cross-sections for the nuclear reactions have been evaluated from the Silberberg and Tsao formalisation. Using the release efficiencies and the cross-sections, the yields have been tabulated.

There are significant gains with the fast target design for the short-lived species. Release efficiencies of over 10% are to be expected for non-sticky particles with decay half-lives of 1-10ms.

Predicted Yields of Selected Radioactive Nuclear Beams from a Thick Target Bombarded by High Energy Protons

1. Introduction

This report has been prepared for the USA Task Force for an advanced radioactive ion beam facility. The work of the report is from a mixture of published material and original work. Most of the data[1] used in preparing the report has not been published, but is available from ISOLDE [1].

2. Scope

The work covers:

a) Calculations of the release parameters of a number of radioactive beams based on data from ISOLDE, CERN, and theoretical modelling of the target. The particles selected by the Task Force and the target materials are shown in Table 1.
b) Predictions of the release efficiencies of the selected beams that would be obtained by optimising the target geometry.
c) Predictions of the yields, based on the release efficiencies, calculated in b), and reaction cross-sections calculated from Silberberg and Tsao [2].

3. Calculations of the Target Release Parameters

3.1 The Release Curve

The time dependant release of radioactive ions from a hot target, bombarded with high energy protons, and followed by a suitable ioniser, generally fit a characteristic release curve [3]. A short (relative to the radioactive decay time of the ion species and their diffusion and effusion time constants in the target and ioniser) pulse of protons on the target gives a current of radioactive ions which initially rises from zero to a peak and then falls, as shown in Figure 1.

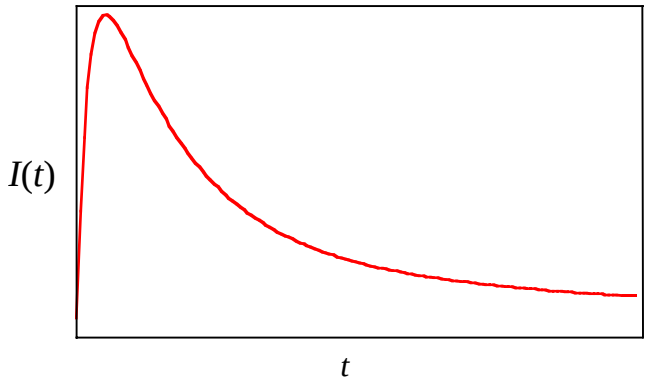

Figure 1. A typical release curve.

[1] Contact Helge Ravn, ISOLDE, CERN, Geneva, Switzerland

Measurements [3] of the release curves from radioactive beam targets have been taken at ISOLDE by putting a single pulse of protons onto the target, transporting a time gated portion of the beam to a tape station and counting the beta decay particles. The number of beta counts, $n(t)$, is plotted as a function of the release time, t, of the gated radioactive beam, measured from the arrival of the proton pulse on target ($t = 0$).

When a proton hits the target it reacts with the atoms and the nuclei, suffering energy loss and scattering. Some of the nuclear interactions will produce a radioactive particle. The production rate of a particular radioactive species depends not only on the proton beam current hitting the target and the cross section for the reaction in the material at the energy, but also on the geometry of the target and the proton beam density distribution. This is due to the details of the scattering and energy loss of the protons and the interaction of secondary particles, such as neutrons, in the target. In addition there may be other indirect ways of producing the particular species, such as through the decay chains of other isotopes.

Once the radioactive particles have been formed, they start to decay at the appropriate fractional rate, λ. The particles also start to diffuse out of the target material. On reaching the surface they are, in principle, free to leave the surface and will in general hit another surface where they have the choice of sticking for some time before leaving or being reabsorbed and diffusing into the target material. The diffusion rates depend on the diffusion constant, which is temperature dependent, hence the requirement for hot targets, and the geometry of the target material. Particles reach the surface more quickly if the material is thin, hence the use of powders and foils.

Assume that the target is devoid of particles initially when the short proton pulse hits the target. Immediately following the pulse, the particles at the surface of the foils start to fill the target void volume. Some of the particles eventually reach the opening into the ioniser, which may be connected via a tube. This tube causes an additional delay in the particles before some of them emerge from the ioniser as ions. Hence the release curve rises from zero at time $t = 0$ to reach a peak and then falls as the diffusion decreases. The effusion of particles within the target and the ioniser is dependent on the temperature and geometry.

For a given element in a given target and ion source at a particular temperature, it is possible to define a probability rate, the release function [3], $p(t)$, for an atom, generated at time $t = 0$, to be released from the ion source. Some of these atoms will be released as ions, due to the action of the ioniser. If the ionisation efficiency for the particular species is ε_i, the ion current as a function of time will be of the form,

$$i(t) = \varepsilon_i \cdot \sigma \cdot n_p \cdot I \cdot g \cdot p(t) \cdot e^{-\lambda \cdot t} \qquad (3.1)$$

where σ is the "thin target" cross section for production of the isotope by the proton beam as it passes through the target, n_p is the number of protons in a pulse (assumed to be much shorter than the decay time of the isotope), I is the input particle beam current and g is a "thick target" geometry factor to take account of secondaries and scattering. Note that all the diffusion and effusion, including temperature, geometry effects and any re-absorption are included in the term $p(t)$. By definition, the integral of $p(t)$, from 0 to ∞, is 1, except where the particles form stable compounds with the target material.

3.2 Theoretical Model of the Release Curve

The transport of particles through the target material, the target void and the ioniser are diffusion process described by Fick's Law [4] with the appropriate boundary conditions. A theoretical model has been made of the diffusion and effusion processes in a foil target, which gives the release function, $p(t)$ [5]:

$$p(t) = \frac{2DE}{dh}\int_0^t \sum_{n=-\infty}^{\infty}(-1)^n \frac{e^{-\frac{(nd)^2}{DT}}}{\sqrt{\pi DT}} \sum_{m=-\infty}^{\infty}(-1)^m \frac{e^{-\frac{(2m+1)^2 s^2}{4E(t-T)}} - e^{-\frac{(2m+1)^2 (h+s)^2}{4E(t-T)}}}{(2m+1)\sqrt{4\pi E(t-T)}}\,dT \qquad (2)$$

where:
D is the diffusion coefficient of the target foil
$2d$ is the thickness of the foil
$2h$ is the length of the target
E is the diffusion coefficient of the target void and the ioniser (effusion)
$2h$ is the length of the target
s is the length of the ioniser
The integral of the double sum is with respect to time, T, from $T = 0$ to $T = t$.

It is often more illuminating to express the equation in terms of the three diffusion time constants:
for the target foil,

$$\tau_D = \left(\frac{2d}{\pi}\right)^2 \frac{1}{D} \qquad (3)$$

the effusion in the target

$$\tau_E = \left(\frac{2h}{\pi}\right)^2 \frac{1}{E} \qquad (4)$$

and the effusion in the ioniser

$$\tau_s = \left(\frac{2s}{E}\right)^2 \frac{1}{E} \qquad (5)$$

which gives the release function,

$$p(t) = \frac{4}{\pi^3}\int_0^t \left[\sum_{n=-\infty}^{\infty}(-1)^n \frac{e^{-\left(n\frac{\pi}{2}\right)^2 \frac{\tau_D}{T}}}{\sqrt{\tau_D}\sqrt{T}}\right]\left[\sum_{m=-\infty}^{\infty}(-1)^m \frac{e^{-\left[(2m+1)\frac{\pi}{4}\right]^2 \frac{\tau_s}{t-T}} - e^{-\left[(2m+1)\frac{\pi}{4}\right]^2 \frac{\left(\sqrt{\tau_s}-\sqrt{\tau_E}\right)^2}{t-T}}}{(2m+1)\sqrt{\tau_E}\sqrt{t-T}}\right] dT \qquad (6)$$

The model was made for the RIST [6] tantalum foil target and a correction must be made for powders [7]. If the powders are spheres of radius d then the time constant for diffusion is 4 times smaller than the foil of thickness $2d$. For a sphere,

$$\tau_d = \left(\frac{d}{\pi}\right)^2 \frac{1}{D} \qquad (7)$$

3.3 Calculation of the Release Parameters

The release parameters, *D*, *E* and *s*, of equation (2) are found by fitting to the equation to the data[2] measured at ISOLDE on the CERN PS at 1 GeV. The accuracy of this data is suspect between targets #050 and #129, because of possible malfunctions of the counting equipment used with the tape station and the beam gate. The most careful studies have been with tantalum targets and the release of lithium. The other particles, ^{25}Na, ^{46}K, ^{80}Rb, and ^{124}Cs, from tantalum, all suffer from a number of unresolved uncertainties in the data and hence in the resultant calculated release parameters.

Initially the data is "hand fitted by eye" using a proprietary mathematics computer package[3] and then a search is made to find the minimum "chi squared" fit [8], using a Fortran programme. Because of the nature of the equation, it is possible for the programme to become locked into a search up the wrong branch. Usually, the initial fit is good enough to prevent this, but a careful check has to be made of the Fortran results.

The results of these calculations are shown in Table 1. The first 2 columns refer to the radioactive isotope and the decay time constant, $\tau = 1/\lambda$. Columns 2 and 3 give the target material and the ISOLDE target reference number. The fifth column states the type of ioniser. The release parameters are given in columns 6-13; the figures in red are the best-fit values of D, E and s; the figures in blue are the corresponding calculated time constants. The last column, highlighted in pale yellow, gives the release probability or release efficiency, as a percentage,

$$Y_p = \int_0^\infty p(t) \cdot e^{-\lambda t} dt \qquad (8)$$

This is the yield probability of particles reaching the exit of the ioniser per particle produced in the target material. The yield probability of obtaining ions from the exit of the ioniser is $Y_p \cdot \varepsilon_i$.

The release curve of ^{11}Li at ISOLDE can not be measured at ISOLDE on the present tape station because it is not a beta emitter. Thus, the values of the release time constants for ^{11}Li have been calculated from ^{8}Li, scaling by the ratio of the square root of their masses. While this is a good approximation for τ_d, measurements of the effusion (τ_e) of ^{7}Li with temperature indicates that surface sticking is important and hence the effusion will not necessarily scale with the masses. However, until an estimate of the dwell time is made, it provides a conservative estimate of τ_e.

The values of D and τ_d for the powder targets have been adjusted to take account of the improved diffusion from spheres as in equation (7).

There is no release curve data available from ISOLDE on the following species selected by the Task Force: Be and Ni from uranium, Sn from tellurium, Kr from niobium or Ga from germanium. Beryllium, gallium, nickel and tin are "sticky" materials and have difficulty effusing through the target; i.e. they have low vapour pressures, or long surface dwell times, at the target temperatures.

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[2] Supplied by Helge Ravn, Head of the ISOLDE Group, CERN. The tantalum target data is from the author's own work at ISOLDE.

[3] Mathcad 7 Professional, MathSoft Inc., 101 Main Street, Cambridge, Massachusetts 02142, USA.

Table 1. Calculated Release Parameters

Particle		Target		Ioniser	Release Parameters								Release
isotope	decay s	material	no:	type	*D* cm²/s	*d* cm	*E* cm²/s	*h* cm	*s* cm	τ_d s	τ_e s	τ_s s	Efficiency %
^{9}Li	1.218	Ta	#050	thermal	1.0E-08	0.0013	389	10	3.84	6.3E+01	1.0E-01	1.5E-02	**8.1**
^{8}Li	1.218	Ta	#129	thermal	2.0E-08	0.0001	286	7.5	2.06	2.0E-01	8.0E-02	6.0E-03	**83.5**
^{11}Li	0.013	Ta	#129	thermal		0.0001		7.5		2.4E-01	9.3E-02	7.1E-03	**2**
^{25}Na	85.263	Ta	#050	thermal	1.5E-07	0.0013	300	10	2.5	4.2E+00	1.4E-01	8.4E-03	**100**
^{25}Na	85.263	Ta	#050	thermal	1.5E-07	0.0013	300	10	2.5	4.2E+00	1.4E-01	8.4E-03	**100**
^{25}Na	85.263	Ta	#050	thermal	8.0E-08	0.0013	900	10	4	7.9E+00	4.5E-02	7.2E-03	**100**
^{25}Na	85.263	Ta	#050	thermal	1.2E-07	0.0013	2500	10	7	5.3E+00	1.6E-02	7.9E-03	**100**
Higher Temperature													
^{40}K	165.910	Ta	#050	thermal	1.0E-06	0.0013	400	10	1.5	6.3E-01	1.0E-01	2.3E-03	**100**
^{80}Rb	49.052	Ta	#50	thermal	1.0E-06	0.0013	80	10	1.5	6.3E-01	5.1E-01	1.1E-02	**100**
^{124}Cs	44.435	Ta	#050	thermal	1.0E-06	0.0013	30	10	0.5	6.3E-01	1.4E+00	3.4E-03	**100**
^{124}Cs	44.435	Ta	#050	thermal	1.0E-06	0.0013	1500	10	1.5	6.3E-01	2.7E-02	6.1E-04	**100**
Higher Temperature													
^{8}Li	1.218	UC_2	#020	thermal	2.5E-10	0.0013	0.18	10	0.01	2.5E+03	2.3E+02	2.3E-04	**0.2**
^{8}Li	1.218	UC_2	#118	thermal	2.5E-10	0.0013	40	10	0.25	2.5E+03	1.0E+00	6.3E-04	**2**
^{40}K	165.910	UC_2	#020	thermal	2.5E-10	0.0013	1000	10	4	2.5E+03	4.1E-02	6.5E-03	**24**
^{40}K	165.910	UC_2	#118	thermal	5.0E-07	0.0013	10000	10	30	1.3E+00	4.1E-03	3.6E-02	**100**
^{79}Ga	41.982	UC_2	#020	thermal	7.3E-08	0.0013	25	10	0.4	8.7E+00	1.6E+00	2.6E-03	**94**
^{200}Fr	23.083	UC_2	#020	thermal	1.7E-07	0.0013	80	10	0.4	3.7E+00	5.1E-01	8.1E-04	**96**
^{9}He	1.161	ThC_2	#027	plasma	1.1E-06	0.0013	9710	10	22.9	5.7E-01	4.2E-03	2.2E-02	**88**
^{9}He	1.161	ThC_2	#027	plasma	2.0E-04	0.0013	176	10	2.7	3.2E-03	2.3E-01	1.7E-02	**100**
Higher Temperature													
^{45}Ar	30.297	ThC_2	#027	plasma	1.1E-07	0.0013	71	10	2.32	5.9E+00	5.7E-01	3.1E-02	**95**
^{99}Kr	46.599	ThC_2	#027	plasma	2.5E-09	0.0013	782	10	18.7	2.5E+02	5.2E-02	1.8E-01	**58**
^{35}Ar	2.554	CaO	#014	plasma	2.5E-09	0.0013	80	10	1.8	2.5E+02	5.1E-01	1.6E-02	**17**

3.4 Discussion of the Results

Measurements of the release curves of tantalum foil targets over the last 3 years give considerable confidence in the results for lithium. In general, however, release curves have not been measured to the degree of detail that is necessary to obtain good results for the release characteristics. The data for ^{46}K was particularly sparse and should be treated with some caution. The measurements from the other target materials, uranium carbide, thorium carbide and calcium oxide, should also be treated circumspectly. Frequently the data has not extended to long enough times to obtain accurate fits for the diffusion coefficients, which contribute mainly to the characteristics of the tails of the release curves. The decay of the particles often makes it difficult to obtain data at long times. The use of stable or long lived isotopes to measure the release parameters is likely to give more accurate results, which can be used for the shorter lived radioactive beams. This approach is currently being pursued with measurements of the release parameters of lithium isotopes [9].

Several measurements of the release curves of ^{25}Na from a tantalum foil target are shown. They show some variation in the release parameters, which gives a good indication of the reliability of the data from some of the more recent results. One of the measurements is taken with the target at a slightly higher temperature than "normal". The values of the time constants, τ_d and $\tau_{e,}$ are smaller in this case, as might be expected. Caesium also shows a significant shorter time effusion constant, τ_e, at a higher temperature. Helium (^{6}He from a thorium carbide target) indicates a shorter τ_d but a longer τ_e. The helium results are not very satisfactory and a large range (a factor of ten) of release parameters are able to fit the data points reasonably well.

The values of the time constant τ_e and τ_s for helium, argon and krypton from the thorium target should vary as the square root of their masses, since they are not "sticky" particles and have zero surface dwell times. The values shown in Table 1 do not agree with this relationship. However, it is possible to select values of the release parameters which do agree and which have reasonably good fits to the data, although they are not the best values (minimum chi squared). This reflects the errors in the data and the latitude of the release parameters to fit the data.

Overall the accuracy of the calculated release parameters is probably no better than a factor of 10 except for some of the more recent data on lithium. However, generally the calculated release efficiencies are considerably more accurate. This is easily seen for the particles with long decay times, by looking at the individual release curves and observing the current approaching zero well before a decay time constant. For those particles with short half-lives, the yield efficiencies are less accurate. However the accuracy of the data from the tantalum targets is good, so the only release efficiencies in any significant doubt are for ^{8}Li from the uranium targets.

3.4.1 The Time Constant for Effusion through the Ioniser, τ_s

The calculated ioniser time constants are in the range 10^{-4} – 10^{-1} s. The time constant of the standard ISOLDE ioniser can be estimated from the conductance, *U*. The conductance of a tube, neglecting end effects, is given by [10],

$$U = \frac{(2r)^3}{6l}\sqrt{\frac{2\pi RT}{M}} \tag{9}$$

where r is the radius and l the length of the tube, R is the gas constant, T the temperature and M the molecular weight.

The diffusion coefficient of the tube is[4],

$$D_s = \frac{U}{V} l^2 \tag{10}$$

and the time constant is,

$$\tau_s = \frac{1}{\pi^2}\frac{V}{U} \tag{11}$$

From the geometry of the ISOLDE thermal ioniser, τ_s is at least 0.6 ms for ^{8}Li and could be as much as 7 ms in certain geometries where part of the target volume should be included in the effective ioniser volume. Target Ta129 is a case where a slightly different model should be applied from the one above, equation (2); the target volume is only partly filled with foils and the ioniser time constant is between 0.6 and 10 ms. All these estimates assume a negligible dwell time on the surfaces.

Thus, the ioniser time constants calculated from the release curves may be small, but are compatible with the values calculated above from the conductance.

3.4.2 The Time Constant for Effusion through the Target, τ_e

In this case it is difficult to make accurate analytical calculations of the conductance through the complicated target geometries. Monte Carlo calculations can help with known geometries, but the uranium, thorium and calcium powders do not have well defined, stable geometries.

Lithium and gallium effusion in the uranium target appears particularly slow and may be a result of sticking to the surfaces. Measurements [9] of lithium from tantalum foil target, Ta129, show that there is a pronounced improvement in effusion (and the diffusion coefficient) with temperature, indicating that lithium is a sticky particle.

3.4.3 The Diffusion Coefficient of the Target Material, *D*

At the temperature of ~2300-2400K where the tantalum targets are usually operated, the diffusion coefficient for lithium is being consistently measured at ~1x10^{-8} cm^2 s^{-1}. The release parameters of other alkali metals are shown in Table 1 to indicate the variation of their diffusion coefficients in tantalum.

There is no diffusion coefficient data in the literature [11] for the particles shown in Table 1, but by comparison with the data that is published, the values found here are not unrealistic. However, trends are difficult, if not impossible to predict from the literature data. The calculations from the release data shown in Table 1 indicate variations of diffusion coefficients in the range 10^{-6}-10^{-10} cm^2 s^{-1}.

[4] Fick's Law expresses the flow of gas in the molecular flow region.

4. Improving the Yields

Reference to (1) indicates that the yield per particle of incoming beam will be influenced by the cross-section for the reaction, the target thickness, the thick target geometry factor and the release efficiency.

The thick target geometry factor is around 2 [12] and will not vary much between targets. The target thickness is a compromise between particle production and the increase in the effusion time. Since the primary beam loses energy passing through the target it becomes less effective in producing the radioactive particles so short targets are not as disadvantaged as they might otherwise be.

If the particle decay time is long relative to the release times then the release efficiency will be 100%. This is illustrated in Table 1 for the cases of ^{6}He, ^{25}Na, ^{45}Ar, ^{46}K, ^{76}Ga, ^{80}Rb, ^{124}Cs and ^{204}Fr. The release efficiency is open to considerable improvement in those cases where the time constants for diffusion and effusion are large or comparable to the decay time constant. The release time constants of the targets shown in Table 1 are in the region of seconds and are too slow to obtain reasonable yields of short-lived particles. Therefore, it is imperative to build fast targets with millisecond time constants.

4.1 Decreasing the Diffusion Time Constant, τ_d

The diffusion time constant given by (3) or (7) can be reduced by selecting the appropriate target material to increase the diffusion coefficient, increasing the operating temperature and reducing the foil or powder particle size. Powders or fine filaments have shorter time constants than foils for the same value of d [7]. Selecting the optimum target materials is difficult, if not impossible, from the existing literature on diffusion coefficients.

4.2 Optimising the Effusion through the Target and Ioniser

First consider a target in the form of a tube filled with material, which contributes negligible impedance to the flow within the tube. The conductance, diffusion coefficient and time constant of a tube, open at one end and closed at the other are given by (9), (10) and (11). The time constant of the tube may be re-expressed as,

$$\tau_t = \frac{3}{4\pi}\frac{l}{r}\sqrt{\frac{M}{2\pi RT}} \tag{12}$$

The formula is accurate for long tubes, but even for short tubes, it is still true that a short, wide tube is beneficial. However, a short target will result in fewer interactions with the primary beam. Thus the tube should have a large bore to keep l/r small.

In practice the ISOLDE target tubes have a relatively small opening to the ioniser. If the area of the aperture is A the conductance through the aperture is,

$$U_A = A\sqrt{\frac{RT}{2\pi M}} \tag{13}$$

Assuming that the conductance of the aperture is much smaller than the conductance of the tube, the time constant for the tube is now,

$$\tau_t = \frac{2r^2 l}{A}\sqrt{\frac{M}{2\pi RT}} \tag{14}$$

or in terms of the tube volume,

$$\tau_t = \frac{2}{\pi}\frac{V}{A}\sqrt{\frac{M}{2\pi RT}} \tag{15}$$

For a fixed exit aperture, A, the volume should be minimised.

The above analysis, although only approximate for a real target, illustrates the need for a large exit aperture to the target volume. In this case, the target volume can be large and both the target length and conductance optimised for yield. The ISOLDE target has dimensions, A = 0.07 cm^2 and V = 63 cm^3, with thermal ioniser of 0.3 cm bore and 3.5 cm length, which gives a time constant of 1.3 ms for ^{8}Li (assumes no surface sticking). Hence, even with the small aperture, the ISOLDE target tube is fast for light radioactive particles with decay times down to ~1 ms.

A real target tube contains the target material in the form of powder, foils, rods or liquid. The conductance through this material is generally the limiting factor in the target time constant. Rather than fill a tube with material, so that particles have to pass through the length of material to reach the aperture to the ioniser, it is better to have a thin layer of the material distributed along the length of the tube. Then, the particles can more rapidly leave the target material and enter the relatively open tube. This is illustrated diagrammatically in Figures 1 and 2.

The conductance through the target material – powder and foils - is difficult to accurately estimate analytically. A Monte Carlo approach is more appropriate [13].

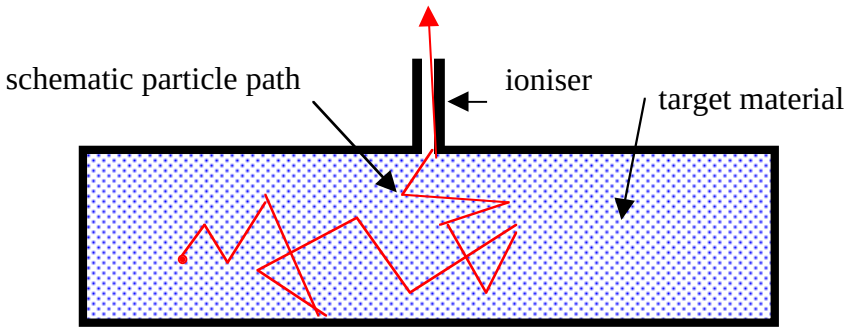

Figure 1. A target tube filled with material (powder) presenting a high impedance to the particle flow.

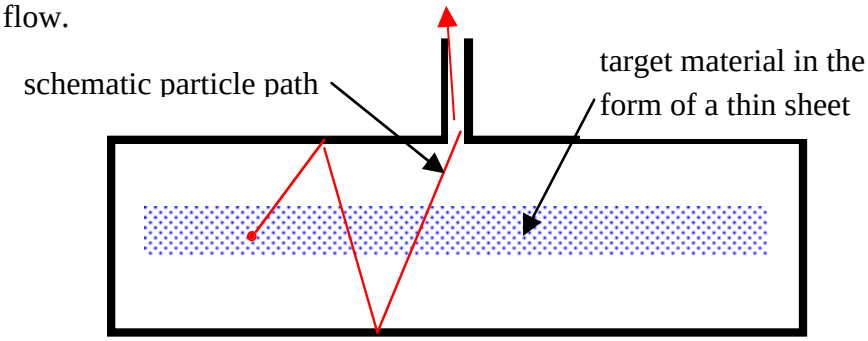

Figure 2. A target tube with a thin sheet of target material presenting an easier path to particle flow.

5. A Fast Tantalum Foil Target

Although powders have higher diffusion rates than tantalum foils of the same thickness as the powder diameter, the stability of the powders at high temperature over an extended time is in some doubt. If the powders coalesce into large clumps the advantages of the high diffusion with small size disappear. A tantalum (or other refractory material) foil target may have the best chance of long term stability at high temperature.

The thinnest tantalum foil currently available is 0.00005 cm thick. Putting this number in (3), gives τ_d = 13 ms for ^{11}Li with $D = 2\text{x}10^{-8}$ cm^2 s^{-1} at a temperature T = 2400 K.

The effusion can be improved by making the target foils as small as possible to allow quick passage into the empty void of the target tube. For example, the value of τ_e found from the ^{8}Li data from target Ta129 is 80 ms. A cross section of this target design is shown in Figure 3. The 0.0002 cm thick tantalum foils rest in a U-shaped holder supported in the centre of the target tube. If the holder was transparent and the foils placed in the transverse plane to the tube axis, the time constant for a particle to effuse from between the foils would decrease approximately by a factor of 16. Halving the dimensions of the foil so that they were in a block of only 0.5 cm square, would produce another improvement of a factor of 4. (Ideally the foils should be in the form of discs rather than squares in this scenario.) Figure 4 illustrates the target design, schematically. The resultant effusion time constant, scaled from the figure given in Table 1, is τ_e = 1.25 ms for ^{8}Li.

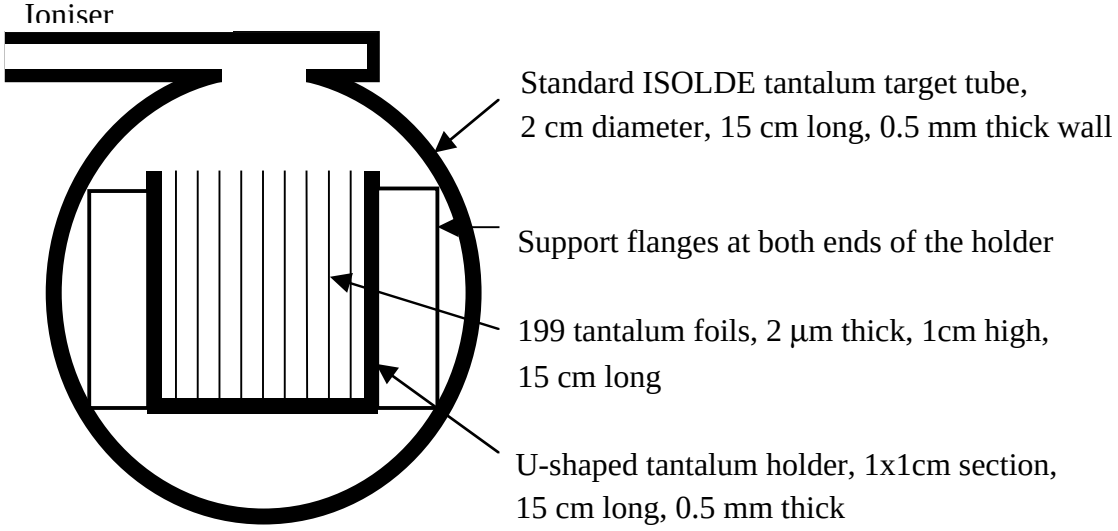

Figure 3. Cross section through the tantalum foil target, Ta129. The foils are longitudinal to the tube axis and the proton beam passes along the axis.

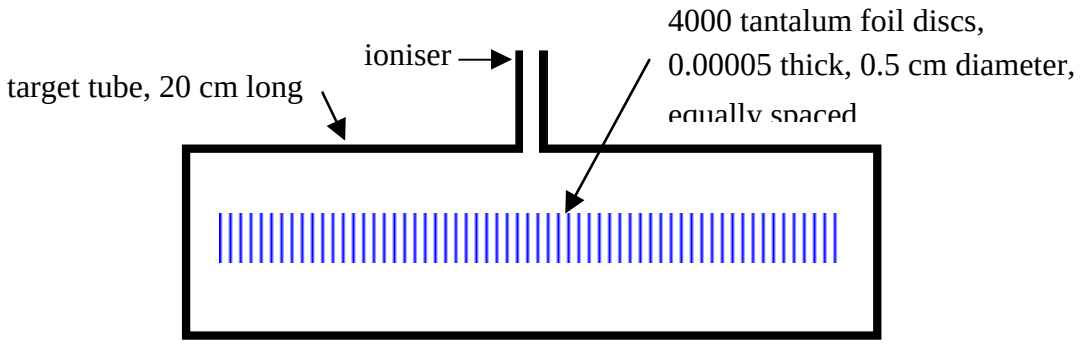

Figure 4. Schematic diagram showing a longitudinal cross-section through the proposed high effusion tantalum foil target. The foils are transverse to the tube axis.

The effusion through the ioniser can be improved by making the conductance high and the target void volume[5] small. The target volume is governed by the need to make the target long enough and to obtain a high conductance in the target void volume. With the present ISOLDE thermal ioniser, the time constant for ^{8}Li through the ioniser is calculated (see section 4.2) to be ~10 ms for target Ta129. The value obtained from the release curve is 6 ms. This could be reduced by increasing the diameter of the ioniser or decreasing the length. Reducing the length from 3.5 cm to 1 cm would decrease τ_s by a factor of 3.5 to give τ_s = 1.7 ms.

Hence it would be possible to obtain diffusion time constants of 10 ms and effusion time constants of a few ms for the light elements. Putting in values for a short-lived isotope, ^{11}Li, of τ_d = 13 ms, τ_e = 2 ms and τ_s = 2 ms, gives a release efficiency of Y_p = 39%. Target Ta129 gave a yield of 7000 particles of ^{11}Li per μC of incoming protons at ISOLDE, with a release efficiency of 2%. Scaling to the proposed fast target would increase the yield 20 times to 140,000/μC. However, the target mass is reduced by a factor of 3 for a 20 cm long target, so the yield would be only 47,000/μC. These calculations are not optimised and further improvements in yield can be expected.

The release efficiency can be predicted as a function of the decay time, τ. This is shown in Figure 5, solid line, with τ_d =13 ms, τ_e = τ_s = 2 ms. Appreciable yields are obtained with decay time constants ≥2 ms.

The unresolved problem is to know the diffusion coeffients of the different elements in tantalum, or other target materials. Table 1 indicates variations from about 10^{-6} to 10^{-10} cm^2 s^{-1}. This would place τ_d in the range of 0.1-1000 ms for the thinnest foil. The release efficiencies for various values of the release times are plotted in Figure 5.

[5] This is the volume not occupied by the block of foils in Fig. 4.

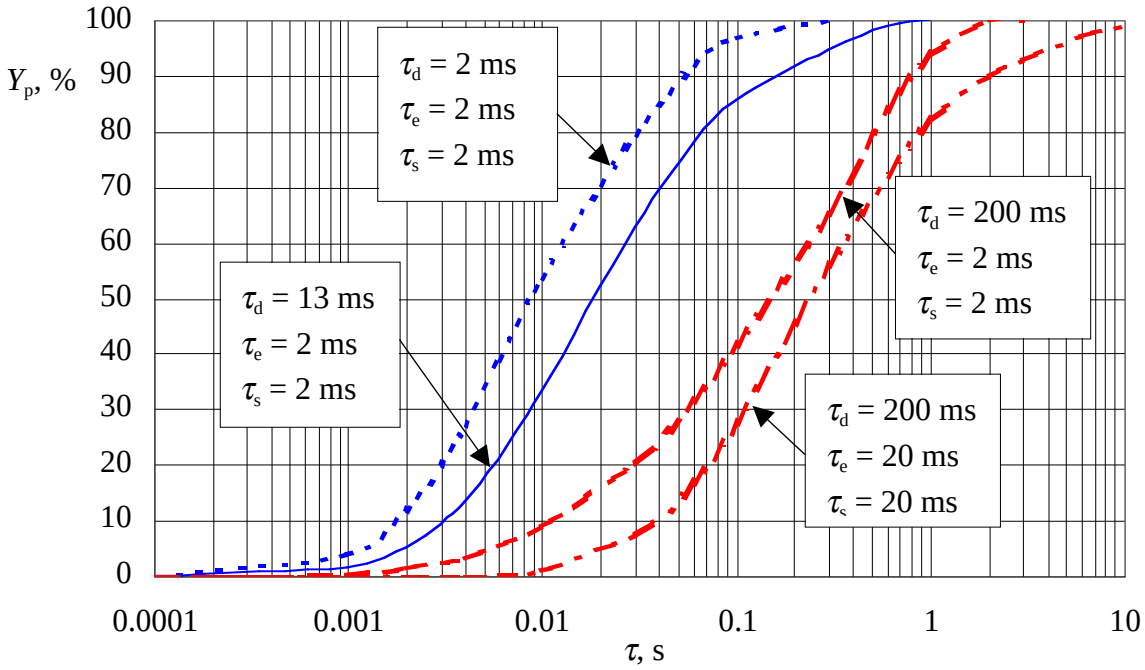

Figure 5. Graph showing the release efficiency, Y_p, as a function of the decay time constant, τ, for different release parameters, as shown in the figure.

6. Other Target Materials

It may be possible to thinly coat tantalum or tungsten foils with a suitable materials to produce both good diffusion and effusion. Alternativly, it may be possible to produce thin coatings on an open graphite matrix (RVC), or other open metal matrix structures. However, it is highly likely that the thin coatings will diffuse[6] into the matrix beneath, to produce target material which is effectively as thick as the matrix. In this case, thin tantalum or tungsten foils, heavily doped with the required material, may still be the best target structure.

Another attractive alternative is to use very fine carbon fibres, less than 1 μm thick, in a loose "cotton wool" structure, which could be coated with uranium, thorium or other materials. At high temperatures, the carbides are likely to be formed uniformly throughout the fibres.

7. "Sticky" Particles

Up to now, it has been assumed that the particles to have zero dwell time on the surfaces. If low vapour pressure, "sticky" or chemically active particles are considered, the effusion times can be significantly increased. In these cases, it will be necessary to change the target materials. Alternatively a chemically active gas can be flowed through the system to produce a molecule which has a short surface dwell time. The release time constants for these cases are difficult to calculate and generally an experimental

[6] They may also chemically combine or form an amalgam.

assessment will be required. Beryllium, gallium, nickel and tin are sticky and it is not possible to assess their release efficiencies without their release curve data.

8. Predicted Yields

The yields of the selected particles can be calculated from (1), knowing the cross-sections and the release parameters. Table 2 shows the cross-sections as calculated[7] from Silberberg and Tsao [2] for 1 GeV protons on calcium, tantalum, thorium and uranium. Little measured data is available for the particles considered in this report. The cross-section of ^{7}Li (1 GeV protons on tantalum) has been calculated from the release measurements taken at ISOLDE and fitting to the theoretical model. Similarly, the cross section for ^{11}Li has been calculated from the yield measurements and the theoretical model for the release efficiency. Both values are found to be very close to the Silberberg and Tsao values, see Table 2. This can be interpreted as a measure of the accuracy of the theoretical model of the release curve and the release curve data.

It can be seen that the known isotopes of the heavier elements do not have very short lifetimes, even at their extremes on the nuclear chart, but their production cross-sections are very small. It would appear that short lifetimes are to be found for the as yet undiscovered particles, but with cross-section so low that the particle flux will be too small for most uses. Hence, for those particles having a reasonable cross-section, the decay times and yield probabilities will be high, even for targets with release times of tens or even hundreds of ms.

It is difficult to predict with any great accuracy the release parameters and the yield efficiencies for all the cases shown in Table 1. The calculated diffusion coefficients *D*, shown in Table 1 have been used with the fast thin foil target design, as indicated in section 5, to obtain the time constant τ_d. The effusion time constants for the fast target design, τ_e and τ_s, have been taken as: 1ms for helium; 2 ms for lithium and sodium. All other heavier particles have been scaled with the square root of their mass taking sodium as the reference with τ_e = 2 ms, i.e. (for non-sticky particles)

$$\tau_e = \tau_s = 2 \cdot \sqrt{\frac{\text{particle mass}}{\text{mass of sodium (24)}}} \quad \text{ms} \tag{16}$$

These values are based on the calculations for the tantalum foil targets. The results of the release efficiencies are shown in Table 2. Also shown are the estimated ionisation efficiencies, ε_i.

For the purpose of calculating the yields, the thickness of the tantalum foil target has been calculated from the dimensions shown in Figure 5. The thorium and uranium targets are assumed to have the foils composed of half thorium, or uranium, and half tantalum to give the same geometry but be a little under half the thickness (see section 6). It is further assumed that the diffusion coefficient for the thorium or uranium is the same as for the ISOLDE carbide targets used in the calculations. This model may be more accurate for the impregnated carbon fibre target, mentioned in section 6. The mass is still assumed to be half the tantalum foil mass, with fibres of about 0.0001 cm diameter, and the effusion times are also taken to be the same as the foil target.

[7] Programme obtained from Helge Ravn, ISOLDE, CERN

Table 2. Calculated Cross-sections and Estimated Yields

Particle		Cross-sections, σ mb				Release Efficiency Y_p, %			Ioniser Efficiency[1]	Yield per µC Y, p/s/µC		
Isotope	Decay Time Constant	Target				Target				Target		
	τ, s	Ca	Ta	Th	U	Ta	Th	U	ε_i %	Ta	Th	U
^{6}He	1.161	1.1	15.4	28.5	30.7	100	100	100	0.5	5.E+06	4.E+06	5.E+06
^{8}He	0.172	1.40E-03	1.03E-01	3.20E-01	3.65E-01	100	100	100	0.5	4.E+04	5.E+04	5.E+04
^{7}Li	stable	5.27	10.56	12.81	13.16	100	100	100	90	7.E+08	3.E+08	4.E+08
	Measured value		9.38									
^{11}Li	0.013	1.10E-04	2.48E-03	5.90E-03	6.60E-03	40		5	90	6.E+04		9.E+03
	Measured value		1.91E-03									
^{11}Be	0.020	6.90E-02	1.60E-01	2.10E-01	2.20E-01		*Sticky*			6.E+06		
^{12}Be	0.035	4.60E-03	2.00E-02	3.00E-02	3.10E-02		*Sticky*			1.E+06		
^{14}Be	0.006	3.62E-05	4.34E-05	8.39E-05	9.11E-05		*Sticky*			8.E+02		
^{27}Na	0.418	1.40E-02	1.10E-02	1.3	1.9	100	100	100	90	7.E+05	4.E+07	5.E+07
^{28}Na	0.044	8.60E-04	1.90E-03	5.40E-01	8.20E-01	86	86	86	90	1.E+05	1.E+07	2.E+07
^{29}Na	0.062	5.30E-05	4.00E-04	2.50E-01	3.80E-01	91	91	91	90	2.E+04	6.E+06	9.E+06
^{30}Na	0.076	1.80E-06	5.40E-05	6.90E-02	1.10E-01	94	94	94	90	3.E+03	2.E+06	3.E+06
^{31}Na	0.025	7.00E-08	5.10E-05	1.40E-01	2.10E-02	77	77	77	90	2.E+03	3.E+06	4.E+05
^{32}Na	0.020	1.50E-09	5.70E-06	3.50E-02	5.30E-02	73	73	73	90	3.E+02	7.E+05	1.E+06
^{33}Na	0.012	4.05E-11	8.20E-07	1.15E-02	1.77E-02	60	60	60	90	3.E+01	2.E+05	3.E+05
^{34}Na	0.008	5.85E-13	7.88E-08	2.65E-03	4.06E-03	48	48	48	90	2.E+00	3.E+04	5.E+04
^{35}Na	0.002	8.45E-15	9.75E-09	8.07E-04	1.24E-03	14	14	14	90	8.E-02	3.E+03	5.E+03
^{45}Ar	30.297	3.90E-05	3.80E-03	1.2	1.7	100	100	100	7	2.E+04	3.E+06	4.E+06
^{46}Ar	11.974	4.50E-06	9.70E-04	8.20E-01	1.2	100	100	100	7	5.E+03	2.E+06	3.E+06
^{49}K	1.876	0	2.50E-04	3.80E-01	5.60E-01	100		76	90	2.E+04		1.E+07
^{50}K	1.068	0	3.90E-05	1.20E-01	1.80E-01	100		65	90	2.E+03		3.E+06
^{51}K	0.527	0	8.00E-06	4.80E-02	7.30E-02	100		50	90	5.E+02		1.E+06
^{52}K	0.151	0	1.20E-06	1.40E-02	2.20E-02	100		29	90	7.E+01		2.E+05
^{53}Ni	0.065	0	6.10E-08	1.00E-04	1.60E-04		*Sticky*					
^{55}Ni	0.274	0	3.70E-06	3.60E-02	1.50E-02		*Sticky*					
^{67}Ni	28.854	0	2.10E-02	4.40E-01	4.20E-01		*Sticky*					
^{62}Ga	0.167	0	4.90E-04	3.40E-02	1.10E-06	100	100	94	10	3.E+03	1.E+05	3.E+00
^{82}Ga	0.866	0	3.70E-07	5.30E-05	4.90E-05	100	100	100	10	3.E+00	2.E+02	1.E+02
^{83}Ga	0.447	0	9.90E-08	7.80E-06	7.20E-06	100	100	100	10	7.E-01	2.E+01	2.E+01
^{71}Kr	0.144	0	9.70E-07	1.10E-02	1.50E-07		62		20		4.E+04	
^{93}Kr	1.861	0	3.20E-06	3.60E-01	3.30E-01		94		20		2.E+06	
^{94}Kr	0.303	0	1.10E-06	2.20E-01	2.00E-01		76		20		1.E+06	
^{95}Kr	1.125	0	2.00E-07	6.50E-02	5.90E-02		61		20		2.E+05	
		0										
^{134}Sn	1.500	0	1.70E-03	1.70E-03	5.7		*Sticky*					
^{201}Fr	0.069	0	0	7.20E-04	4.10E-03		100	81	90	0	2.E+04	9.E+04
^{202}Fr	0.491	0	0	1.60E-03	8.90E-03		100	100	90	0	4.E+04	2.E+05
^{203}Fr	0.793	0	0	4.60E-03	2.50E-02		100	100	90	0	1.E+05	7.E+05
^{204}Fr	3.030	0	0	8.70E-03	4.70E-02		100	100	90	0	2.E+05	1.E+06

[1] Data provided by Helge Ravn, CERN

The last three columns (highlighted) of Table 2 show the estimated yields in particles per second per μC of 1 GeV protons on the target. The calcium target is not listed since it appears to give no advantages over tantalum, thorium or uranium, for the particles considered.

The values of release efficiency and yield in red have been made by a (hopefully) judicious guess at the release efficiency. For the cases where the decay time is long (seconds) and the release efficiency is likely to be 100%, there is a good chance of accuracy. The sodium values are more problematic; it is assumed that the diffusion coefficients are the same as for tantalum. However, it was considered worthwhile to make a guess because the thorium and uranium cross-sections are large compared to those of tantalum and hence the yields could be important.

There are no release curves for beryllium and it is likely to be a sticky particle, since it has a high boiling point, 2743 K. However, the ISOLDE *Yellow Book* [14] gives a yield of 20000 p/s/μC for ^{11}Be from a tantalum foil target bombarded with 910 MeV ^{3}He ions. The yield of beryllium isotopes from the fast tantalum target, bombarded with 1 GeV protons was estimated as follows:

i) assume that the production cross section for 910 MeV ^{3}He is similar to 300 MeV protons ($\sigma = 1.8\text{x}10^{-2}$ mb) – but there are 3 protons (so $\sigma = 5.4\text{x}10^{-2}$ mb) – then scale to 1GeV (σ = 1.6x10-1 mb at 1 GeV, scaling factor = 16/5.4 = 3);
ii) assume that the release efficiency for the fast target can be improved by the same factor as ^{11}Li (x1000);
iii) scale the other isotopes (^{12}Be and ^{14}Be) by their cross-sections;
iv) adjust the release efficiency for the different decay times.

It should be noted that the target is optimised for the shortest decay times. Therefore, yields of particles with decay times greater than the release times, can be significantly improved by making the target foils thicker.

Finally, Table 3 summarises the predicted particle yield currents with 100 μA of 1 GeV protons on the targets of tantalum, thorium and uranium.

9. Discussion of Predicted Yields

Tables 2 and 3 summarise the predicted yields from tantalum, thorium and uranium targets specially designed for fast release. For tantalum targets, the accuracy of the figures is considered to be within a factor of 2 for lithium, and within a factor of 10 for the other particles. The results for the thorium and uranium target are conditional on the ability to built thin foil or carbon fibre targets of these materials. Generally the figures are considered to be conservative.

The release efficiencies are 100%, except for the lighter short half-life particles. This is as expected (see section 8) since there are no recorded short-lived (less than ~100 ms) heavy particles. Even for the lighter particles, release efficiencies of over 10% are predicted for half-lives below 10 ms.

Table 3. Particle Yield Currents for 100 μA of 1 GeV Protons on Target

Particle		Particle Current for 100 μA pps			ISOLDE *Yellow Book* [14] Measurements[1]		
Isotope	Decay Time Constant	Target			Target		
	τ , s	Ta	Th	U	Ta	Th	U
^{6}He	1.161	5.E+08	4.E+08	5.E+08	6.E+06	3.E+08	
^{8}He	0.172	4.E+06	5.E+06	5.E+06		1.E+07	
^{11}Li	0.013	6.E+06		9.E+05	5000 [2]		1.E+03
^{11}Be	0.020	6.E+08			200000 [3]		
^{12}Be	0.035	1.E+08					
^{14}Be	0.006	8.E+04					
^{27}Na	0.418	7.E+07	4.E+09	5.E+09			3.E+07
^{28}Na	0.044	1.E+07	1.E+09	2.E+09			1.E+06
^{29}Na	0.062	2.E+06	6.E+08	9.E+08	3.E+04	2.E+05	5.E+05
^{30}Na	0.076	3.E+05	2.E+08	3.E+08	1.E+03		6.E+04
^{31}Na	0.025	2.E+05	3.E+08	4.E+07			7.E+03
^{32}Na	0.020	3.E+04	7.E+07	1.E+08			7.E+02
^{33}Na	0.012	3.E+03	2.E+07	3.E+07			9.E+02
^{34}Na	0.008	2.E+02	3.E+06	5.E+06			3.E+02
^{35}Na	0.002	8.E+00	3.E+05	5.E+05			
^{45}Ar	30.297	2.E+06	3.E+08	4.E+08			
^{46}Ar	11.974	5.E+05	2.E+08	3.E+08			
^{49}K	1.876	2.E+06		1.E+09		4.E+05	2.E+06
^{50}K	1.068	2.E+05		3.E+08			2.E+05
^{51}K	0.527	5.E+04		1.E+08			3.E+04
^{52}K	0.151	7.E+03		2.E+07			7.E+02
^{62}Ga	0.167	3.E+05	1.E+07	3.E+02			
^{82}Ga	0.866	3.E+02	2.E+04	1.E+04			
^{83}Ga	0.447	7.E+01	2.E+03	2.E+03			
^{71}Kr	0.144		4.E+06				
^{93}Kr	1.861		2.E+08			2.E+08	
^{94}Kr	0.303		1.E+08			3.E+07	
^{95}Kr	1.125		2.E+07			2.E+06	
^{201}Fr	0.069	0	2.E+06	9.E+06			1.E+02
^{202}Fr	0.491	0	4.E+06	2.E+07			7.E+03
^{203}Fr	0.793	0	1.E+07	7.E+07		4.E+06	1.E+05
^{204}Fr	3.030	0	2.E+07	1.E+08		4.E+07	

Values in RED are estimated.

[1] Yields for 600 MeV protons scaled to 100 μA and corrected to a target thickness of ~10 g cm^{-2}

[2] Yield measured with 1 GeV protons on a standard ISOLDE tantalum rolled foil target, scaled to 100 μA and corrected to a target thickness of ~10 g cm^{-2}.

[3] Yield from 910 MeV ^{3}He on tantalum foil target

Comparison (see Table 3) with the yields quoted in the ISOLDE *Yellow Book* [14] shows the gains of the fast foil target for the short-lived isotopes, as would be expected. The ISOLDE targets are much slower, with diffusion and effusion time constants of seconds (see Table 1), than the proposed fast target,.

The yields of beryllium, nickel and tin are hard to predict because of lack of data and the particles stick to the surfaces. A sound solution to the problem of surface sticking is required. Flowing suitable gases through the target to produce non-sticky molecules can be a solution, but there is insufficient data to predict yields by this method.

Further improvements in the reduction of the effusion release times may be achieved by incorporating the ioniser into the target and by suitable electric fields in the target to accelerate the particles in the direction of the outlet aperture [15]. The action of a plasma discharge within the target could also remove sticky particles by sputtering. However, these are only ideas at present and have yet to be tested. At best, a release efficiency of 10-30% might be expected for particles with a 1 ms decay time constant (0.7ms half-life). This is with the ioniser incorporated in the target, $\tau_s = 0$, the target effusion time constant reduced to $\tau_e = 1$ ms by the action of the electric field and the thinnest foils with $\tau_d = 1$-10 ms.

Finally, the ionisation efficiencies for the plasma source are often low. In principle, significant gains are possible in this area. However, care must be taken not to unduly lengthen the effusion time through the ion source.

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